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COMPUTER DESIGN OF A THERMOELECTRIC PULMONARY AIR CONDENSER WITH THERMOSTATING OF COLLECTED CONDENSATE

A new design of a thermoelectric pulmonary air condenser is proposed, in which an additional thermostated chamber is used to collect condensed moisture. This allows maintaining the temperature of the collected condensate at a given permissible level to prevent its hypothermia and standardize the storage conditions. The physical model and computer model of the device are presented, the distribution of temperature and velocity of air movement in the condensate collection tube is determined depending on the temperatures of the working and additional chambers, as well as humidity, temperature and volume of exhaled air. The results of calculations of the cooling efficiency of thermoelectric modules, necessary to ensure the specified modes of operation of the device, are given. Bibl. 7, Fig. 9.

Key words: diagnostics, coronavirus, condensate, exhaled air, thermoelectric cooling.

Introduction

Diagnostic testing plays a crucial role in overcoming the pandemic of the coronavirus disease COVID-19, caused by the severe acute respiratory syndrome coronavirus SARS-CoV-2. Rapid and accurate diagnostic tests are mandatory for identification and treatment of infected individuals, contact tracing, epidemiologic characterization, and healthcare decision-making. Modern diagnostic testing for the coronavirus disease COVID-19 is based on the detection of the SARS-CoV-2 coronavirus in swab samples from the nasopharynx by the reverse transcription polymerase chain reaction (RT-PCR) method. However, this test is associated with an increased risk of viral spread and environmental contamination and shows a relatively low sensitivity due to technical shortcomings of the sampling method. Given that COVID-19 is transmitted through aerosols and droplets exhaled by humans, the detection of SARS-CoV-2 in pulmonary condensate may serve as a promising non-invasive diagnostic method. This method is proposed in the works of scientists from Japan, the USA, Ireland and other countries as a more sensitive and reliable method of detecting COVID-19 [1 – 3]. Generally, special devices, namely condensers, are used to collect condensate, in which vapors from the air exhaled by a person condense at a temperature from 0 to -70 °C and are collected in a container for further research by the RT-PCR method [4]. Lowering the condensation temperature makes it possible to speed up obtaining the amount of biological material required for research. At the same time, the operating temperatures of condensers that use ice at 0°C or compressor cooling down to -20°C are not efficient enough and do not provide a high condensation rate. In addition, compressor condensers are complex, expensive, with insufficient control and maintenance of operating temperature, as well as the presence of dangerous refrigerants. The temperature of -70 °C, which is achieved using dry ice (solid CO2), is excessive and extremely inconvenient for operation, which drastically reduces the possibilities of using this method. The paper [5] gives the results of computer design of a thermoelectric device for collecting exhaled air condensate with precisely regulated condensation temperatures below -20 °C and close to -70 °C without the use of dry ice

However, in some cases, it is also important that the collected condensate does not freeze and is not supercooled, because this can negatively affect the results of research [6]. For such a case, a device scheme with a separate thermostated chamber, in which condensed moisture is collected, can be used.

The purpose of the work is computer design and development of the design of a thermoelectric pulmonary air condenser with thermostatng of the collected condensate.

Physical and computer models of a thermoelectric pulmonary air condenser

Physical model of a cooling unit for a thermoelectric pulmonary air condenser with a separate thermostated chamber in which condensed moisture is collected, is shown in Fig. 1.

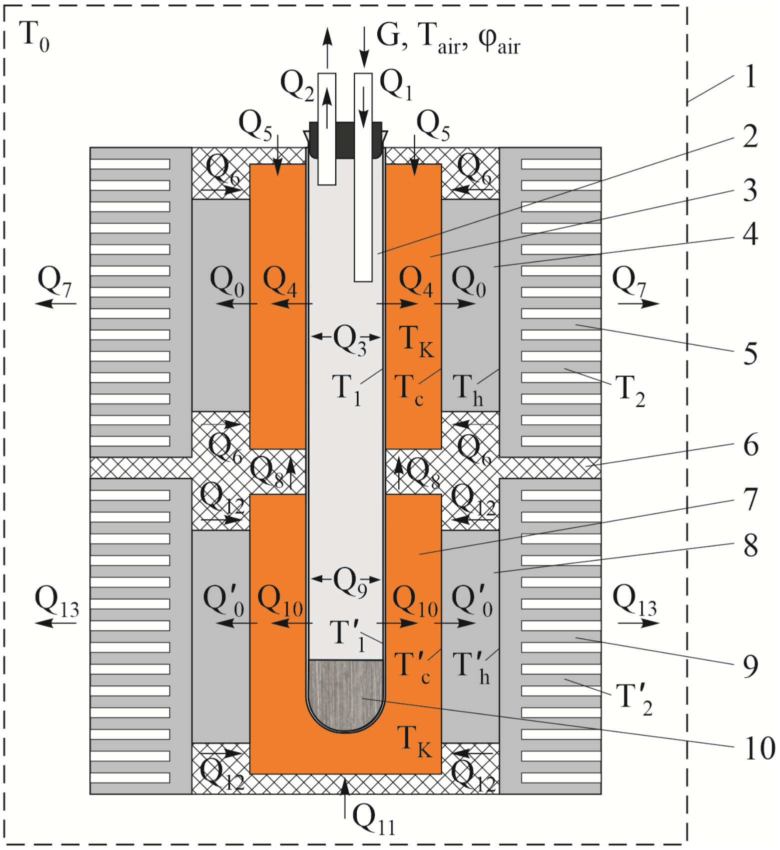


Fig. 1 – Physical model of a cooling unit for a thermoelectric device for collecting condensate from the air exhaled by a person: 1 – thermostat (device body); 2 – test tube for collecting condensate; 3 – working chamber; 4, 8 – thermoelectric modules; 5, 9 – air heat exchangers; 6 – thermal insulation; 7 – additional cooling chamber; 10 – collected moisture

In Fig. 1:

G, T_{air}, φ_{air} – consumption, temperature and relative humidity of air exhaled by the patient;

Q_1 – heat flow entering the tube for collecting condensate together with the air exhaled by the patient;

Q_2 – heat flow removed from the test tube to the environment;

Q_3, Q_9 – heat released in the test tube during the condensation of exhaled air vapours;

Q_4 – heat flow transferred from the walls of the test tube to the working cooling chamber;

Q_5 –inflow of heat to the working cooling chamber from the environment through thermal insulation;

Q_6 –inflow of heat to the working cooling chamber from the air heat exchangers through thermal insulation;

Q_7 – heat flow removed from the air heat exchangers of the working cooling chamber to the environment;

Q_8 – inflow of heat from the additional cooling chamber to the working chamber through thermal insulation;

Q_{10} – heat flow transferred from the test tube walls to additional cooling chamber;

Q_{11} – inflow of heat to the additional cooling chamber from the environment through thermal insulation;

Q_{12} – inflow of heat to the additional cooling chamber from the air heat exchangers through thermal insulation;

Q_{13} – heat flow removed from the air heat exchangers of the additional cooling chamber to the environment;

Q_0, Q'_0 – cooling capacity of thermoelectric modules of the working and additional cooling chambers;

T_1, T'_1 – temperatures of test tube walls in the working and additional cooling chambers;

T_c, T'_c – cold side temperature of thermoelectric modules of the working and additional cooling chambers;

T_h, T'_h – hot side temperature of thermoelectric modules of the working and additional cooling chambers;

T_2, T'_2 – temperature of air heat exchangers of the working and additional cooling chambers;

T_0 – temperature of the environment (device body).

A computer model of the device was built using the Comsol Multiphysics software package. In doing so, the following program modules were used.

1. *Turbulent Flow*. Allows simulating turbulent flow using a wide range of turbulence models, as well as Large Eddy Simulation (LES) and Detached Eddy Simulation (DES). The eight turbulence models differ in how they model flow near walls, the number of additional variables that are calculated, and what these variables represent. All these models supplement the Navier-Stokes equation with an additional eddy viscosity term of turbulence, but they differ in the way it is calculated
2. *Heat Transfer in Solids*. Allows solving equation

$$\rho C_p\left(\frac{\partial T}{\partial t} + \mathbf{u}_{\text{trans}} \cdot \nabla T\right) + \nabla \cdot (\mathbf{q} + \mathbf{q}_\mathrm{r}) = -\alpha T : \frac{dS}{dt} + Q$$

where:

- ρ – density (SI unit: kg/m^3);
- C_p – specific heat capacity at constant pressure (SI unit: J/(kg·K));
- T – absolute temperature (SI unit: K);
- $\mathbf{u}_{\text{trans}}$ – vector of translational speed (SI unit: m/s);
- $\mathbf{q}$ – heat flow due to thermal conductivity (SI unit: W/m^2);
- $\mathbf{q}_\mathrm{r}$ – heat flow due to radiation (SI unit: W/m^2);
- α – coefficient of thermal expansion (SI unit: 1/K);

- *S* – the second Piol-Kirchhoff stress tensor (SI unit: Pa);
- *Q* comprises additional sources of heat (SI unit: W/m^3).

For a stationary problem, the temperature does not change with time and conditions, and derivatives disappear with time.

3. *Moisture Transfer in Air*. Interface of moisture transfer in air solves the equation

$$M_v \frac{\partial c_v}{\partial t} + M_v \mathbf{u} \cdot \nabla c_v + \nabla \cdot \mathbf{g} = G$$

in which the change in moisture content is expressed through the transfer of vapor concentration, which itself can be expressed as the product of the molar mass of water, the relative humidity, and the vapour saturation concentration:

$$\mathbf{g} = -M_v D \nabla c_v$$

$$c_v = \phi c_{sat}$$

with the following material properties, fields and source:

- M_v (SI unit: kg/mole – molar mass of water vapour;
- φ (dimensionless) – relative humidity;
- c_{sat} (SI unit: mole/m^3) – vapour saturation concentration;
- *D* (SI unit: m^2/s) – coefficient of vapour diffusion in air;
- u (SI unit: m/s) – air velocity field;
- *G* (SI unit: kg/(m^3·s)) – moisture source (or absorber).

Transfer of vapor concentration occurs by convection and diffusion in moist air. It is assumed that moisture consists only of vapour. In other words, the concentration of the liquid is zero.

4. *Heat Transfer in Moist Air*.. It is used to model heat transfer in moist air by convection and diffusion using thermodynamic properties defined as a function of the amount of vapor in moist air.

5. *Multiphysics. Nonisotermal Flow*. Non-isothermal flow refers to fluid flows with non-constant temperatures. When a liquid undergoes a change in temperature, its material properties, such as density and viscosity, change accordingly. In some situations, these changes are large enough to have a significant effect on the flow field. And since the liquid transfers heat, the temperature field, in turn, is affected by changes in the flow field.

6. *Multiphysics. Moisture Flow.* The Moisture Flow multiphysics coupling is used to model fluid flows where fluid properties (density, viscosity) depend on moisture content. The Moisture Flow interface allows you to maintain vapor concentration, mass and momentum in the air. It synchronizes the functions of the moisture transport and fluid flow interfaces when a turbulent flow regime is defined.

7. *Multiphysics. Heat and Moisture*. This multiphysics relationship is used to model coupled heat and moisture exchange processes in various environments, including moist air by modeling moisture transport by vapor diffusion and convection and heat transfer by conduction and convection. The thermodynamic properties of moist air depend on the moisture content, while the temperature is used to define the saturation conditions for vapor concentration. This module synchronizes the functions of heat transfer and moisture transport interfaces:

- determines the relative humidity ϕw (with appropriate temperature and pressure) to adjust the appropriate input to the Wet Air function of the heat transfer interface;
- determines the temperature to set the model input data in the functions of the moisture transport interface;

- calculates the latent heat source due to evaporation and condensation fluxes on surfaces and adds it to the heat transfer equation.

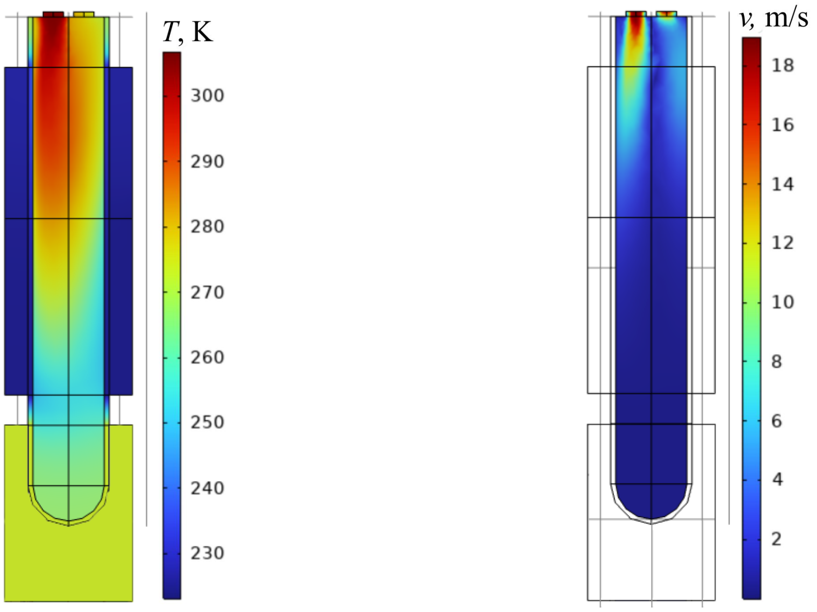
The created computer model makes it possible to calculate temperature distributions in the working chamber and the tube for collecting condensate from air exhaled by a person, the velocity of air in the tube, and determine the amount of condensate received.

Computer simulation results

The used boundary conditions of the computer model correspond to the physical model shown in Fig. 1. In this case, the average consumption of incoming air is determined by the number of exhalations per minute and the volume of exhaled air. It is known from the literature that the typical number of exhalations per minute is between 12 and 21. In doing so, the volume of exhaled air is equal to 0.3 - 0.7 l. The work [7] shows the results of experimental studies of the temperature and relative humidity of the exhaled air: the temperature range of exhaled air is 31.4-35.4 °C for participants from Haifa and 31.4 - 34.8 °C for participants from Paris, and the exhaled air relative humidity range is 65.0-88.6 % and 41.9-91.0 % for Haifa and Paris. participants respectively. That is, the temperature of air exhaled by people is in the range of 34-35 °C, and the relative humidity of the air is high, 90 % and above, regardless of geographical location.

The above ranges of input parameters were used for calculations. Fig. 3 shows a typical temperature distribution in a condensate collection tube. For this case, the following input parameters were used: working chamber temperature – 223.15 K; the temperature of the additional chamber - 273.15 K; the temperature of the air exhaled by a person - 306.65 K; humidity of exhaled air – 90 %; the average air velocity at the entrance to the test tube is equivalent to 18 exhalations per minute with an air volume of 0.5 l.

The computer model makes it possible to obtain similar distributions for other values of the input parameters, to build the dependences of the amount of collected condensate and its temperature on these parameters, to determine the requirements for thermoelectric modules and to optimize the design and operating modes of the device.



a) *b)*

Fig. 3. Typical distributions of temperature (a) and air velocity (b) in the test tube for collecting exhaled air condensate

Figs. 4, 5 give an example of the results of computer calculations of the condensate collection velocity V_K (in ml per minute) and the thermal power Q_0 that must be removed from the working chamber at different values of the working chamber temperature T_K, relative humidity of the exhaled air φ_{air}, temperature and exhaled air consumption.

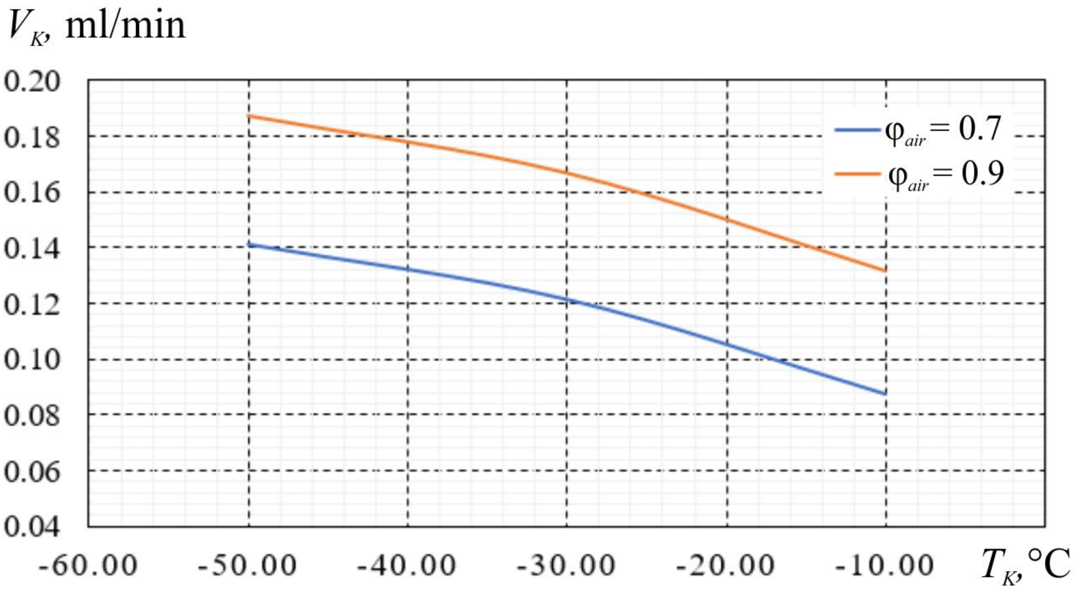


Fig. 4. Dependences of the condensate collection velocity V_K on the temperature in the working chamber T_K for different values of the relative humidity of the exhaled air (the temperature of the additional cooling chamber is 0 °C; the temperature of the exhaled air is 33.5 °C; the air consumption is equivalent to 18 exhalations per minute with an exhalation volume of 0.5 l)

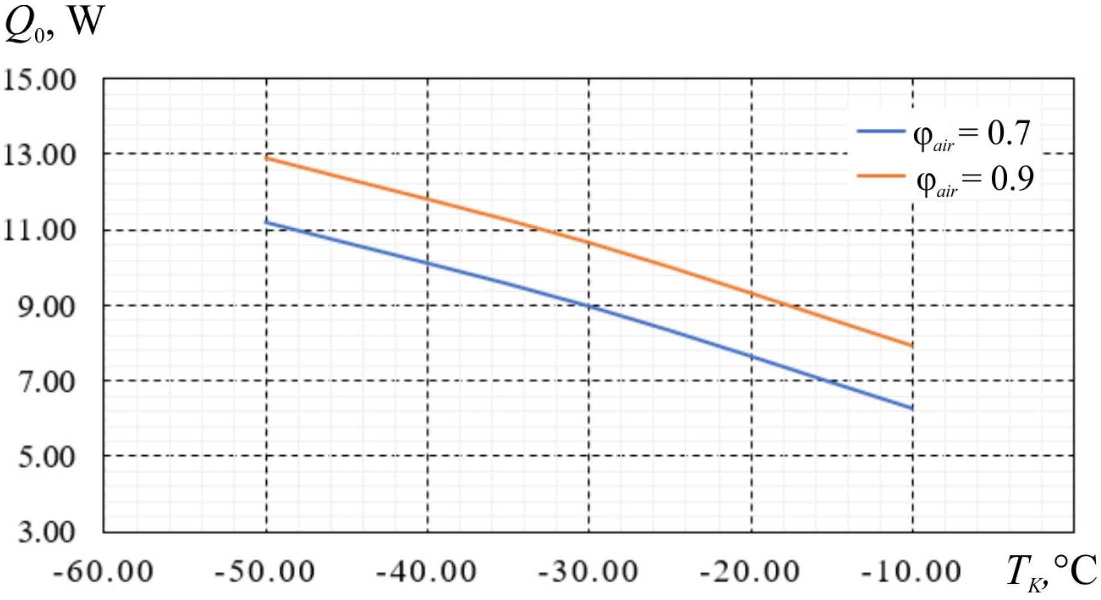


Fig. 5. Dependences of the thermal power Q_0, which must be removed from the working chamber, on the temperature in the working chamber T_K for different values of the relative humidity of the exhaled air (the temperature of the additional cooling chamber is 0 °C; the temperature of the exhaled air is 33.5 °C; the air consumption is equivalent to 18 exhalations per minute with an exhalation volume of 0.5 l)

Fig. 6 shows the dependence of the condensate collection velocity V_K on the exhaled air consumption G for different temperature values of the working chamber T_K (at an exhaled air temperature of 33.5 °C and its relative humidity of 90%), and Fig. 7 – the corresponding dependence of the thermal power Q_0, which must be removed from the working chamber to ensure such operating modes.

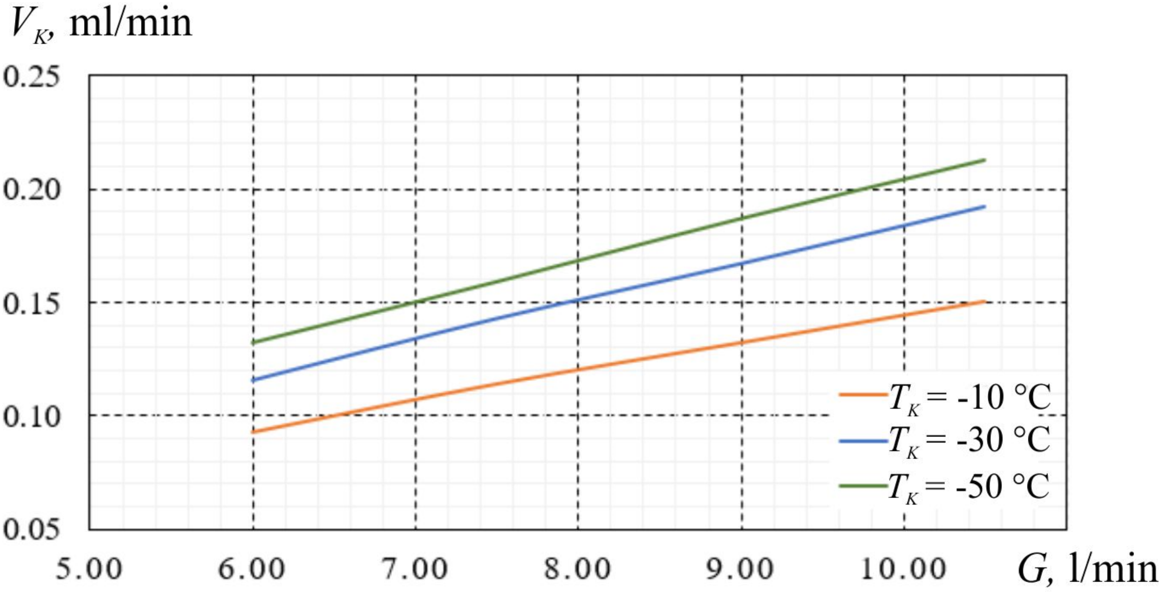


Fig. 6. Dependences of the condensate collection velocity V_K on the exhaled air consumption G for different temperature values of the working chamber T_K (at the temperature of the exhaled air 33.5 °C, its relative humidity 90 % and the temperature of the additional cooling chamber – 0 °C)

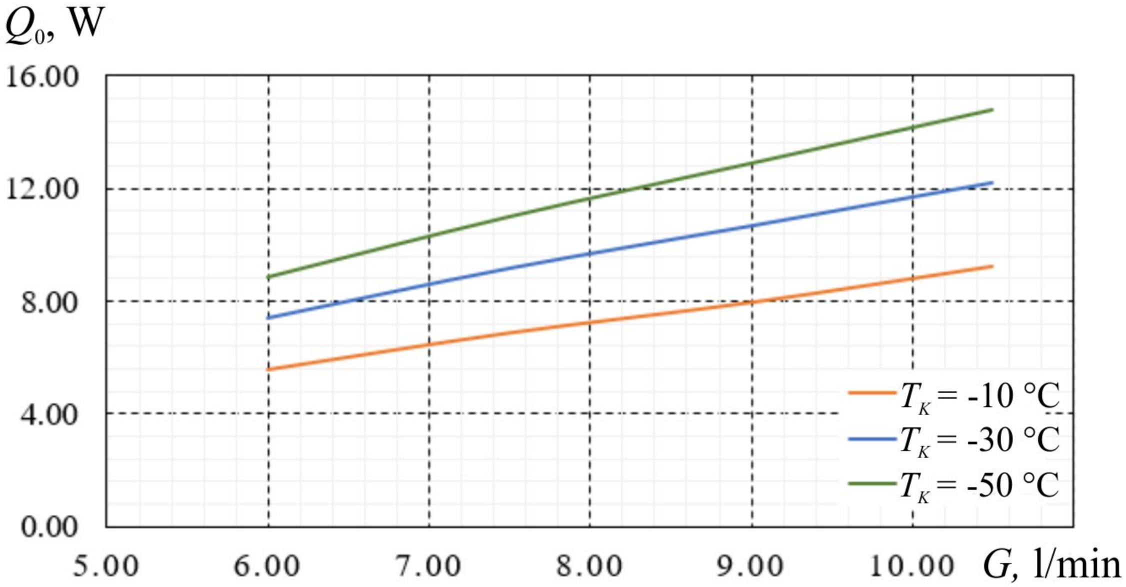


Fig. 7. Dependences of the thermal power Q_0which must be removed from the working chamber, on the exhaled air consumption G for different values of the temperature of the working chamber T_K (at the temperature of the exhaled air 33.5 °C, its relative humidity 90 % and the temperature of the additional cooling chamber – 0 °C)

Based on the results of computer simulation, to ensure the necessary operating modes of a thermoelectric device for collecting condensate from the air exhaled by a person, one module, for example, the Altec-2 type produced by the Institute of Thermoelectricity, is sufficient to maintain the temperature of the working chamber at the specified cooling capacity of the module

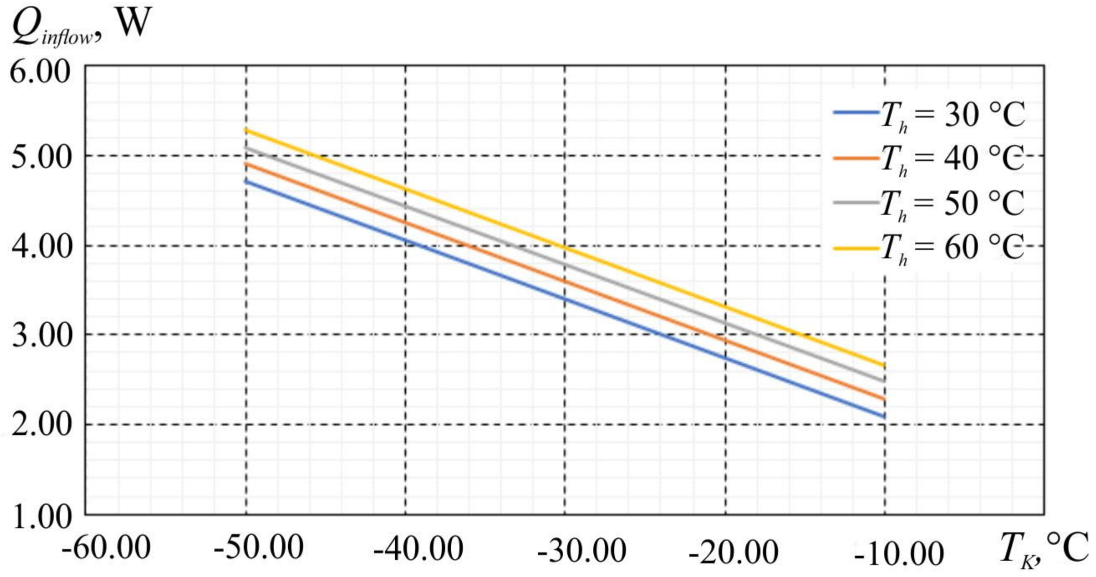


Fig. 8. Dependences of heat inflows from the environment to the working chamber Q_{inflow} on the temperature of the working chamber T_K for different values of the hot side temperature of the thermoelectric module (the temperature of the additional chamber is -0 °C)

Using computer simulation in Comsol Multiphysics for the physical model shown above in Fig. 1, the amounts of heat inflow from the environment Q_{inflow}, are calculated which are composed of heats: Q_5 – heat inflow to the working chamber from the environment through thermal insulation, Q_6 – heat inflow into the working chamber from air heat exchangers through thermal insulation, and Q_8 – heat inflow from additional cooling chamber to the working chamber due to thermal insulation. The results of the calculations are shown in Fig. 8.

Taking into account the maximum values of the thermal power Q_0, which must be removed from the working chamber for different values of its temperature T_K, the dependence of the total cooling capacity of the thermoelectric module of the working chamber Q_{0total} on its temperature was obtained for different values of the hot side temperature of the module (Fig. 9).

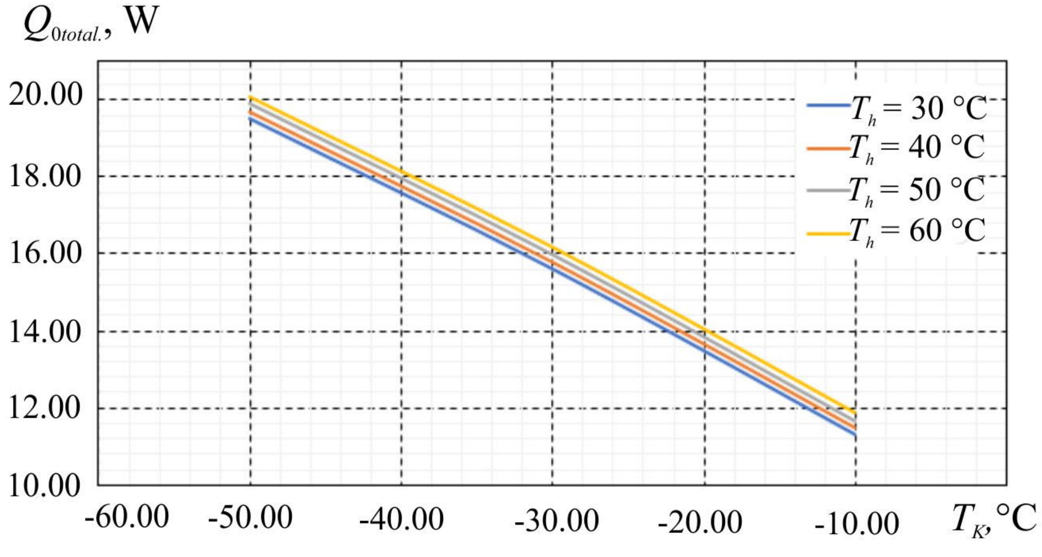


Fig. 9. Dependences of cooling capacity of thermoelectric module of the working chamber $Q_{0total.}$ on its temperature T_K for different hot side temperature values of thermoelectric module (the temperature of additional chamber –0 °C)

Thus, in order to ensure the necessary modes of the working chamber of the device (temperature below -20 ℃) with a power consumption of the Altec-2 thermoelectric module of about 145 W and a cooling capacity of up to 20 W, a heat exchange system is required, which will remove about 165 W of heat with a temperature difference relative to the environment not above 15 ℃. At the same time, additional chamber thermostating does not require such low temperatures and can be performed using standard thermoelectric cooling modules.

The presented results are the basis for the further development of the design of a thermoelectric device for collecting condensate from the air exhaled by a person.

Conclusions

1. A physical and computer model of a thermoelectric pulmonary air condenser was built, in which an additional thermostated chamber was used to collect condensed moisture, which. allows maintaining the temperature of the collected condensate at a given level, different from the temperature in the working cooling chamber.
2. The dependences of temperature distributions and air velocity in a condensate collection tube on the temperatures of the working and additional chambers, as well as the humidity, temperature and volume of exhaled air, and the amount of heat inflow from the environment were calculated.
3. It has been established that reducing the temperature of the working chamber to -50 ℃ (at an additional chamber temperature of 0 ℃) makes it possible to achieve a condensate collection velocity of 0.13 - 0.21 ml/min. At the same time, to ensure the required operating mode, the cooling capacity of the thermoelectric modules of the working chamber should be 19 - 20 W.

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Submitted: 29.03.2023

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КОМП'ЮТЕРНЕ ПРОЄКТУВАННЯ ТЕРМОЕЛЕКТРИЧНОГО КОНДЕНСАТОРА ЛЕГЕНЕВОГО ПОВІТРЯ З ТЕРМОСТАТУВАННЯМ ЗІБРАНОГО КОНДЕНСАТУ

Запропоновано нову конструкцію термоелектричного конденсатора легеневого повітря, у якій використано додаткову термостатовану камеру для збирання конденсованої вологи. Це дозволяє підтримувати температуру зібраного конденсату на заданому допустимому рівні для запобігання його переохолодженню і стандартизації умов зберігання. Наведено фізичну модель та комп'ютерну моделі приладу, визначено розподіли температури та швидкості руху повітря у пробірці для збирання конденсату в залежності від температур робочої та додаткової камер, а також вологості, температури та об'єму видихуваного повітря. Наведено результати розрахунків холодопродуктивності термоелектричних модулів, необхідної для забезпечення заданих режимів роботи приладу. Бібл. 7, рис. 9.

Ключові слова: діагностика, коронавірус, конденсат, видихуване повітря, термоелектричне охолодження.

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Submitted: 29.03.2023